SAND2024-13446J

Received: 22 December 2023 | Revised: 15 August 2024 | Accepted: 5 September 2024

DOI: 10.1002/wat2.1759

PRIMER

WIREs WATER WILEY

The water–climate nexus: Intersections across sectors

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Edited by: Jan Seibert, Editor-in-Chief

Abstract

Water security and climate change are important priorities for communities and regions worldwide. The intersections between water and climate change extend across many environmental and human activities. This Primer is intended as an introduction, grounded in examples, for students and others considering the interactions between climate, water, and society. In this Primer, we summarize key intersections between water and climate across four sectors: environment; drinking water, sanitation, and hygiene; food and agriculture; and energy. We begin with an overview of the fundamental water dynamics within each of these four sectors, and then discuss how climate change is impacting water and society within and across these sectors. Emphasizing the relationships and interconnectedness between water and climate change can encourage systems thinking, which can show how activities in one sector may influence activities or outcomes in other sectors. We argue that to achieve a resilient and sustainable water future under climate change, proposed solutions must consider the water–climate nexus to ensure the interconnected roles of water across sectors are not overlooked. Toward that end, we offer an initial set of guiding questions that can be used to inform the development of more holistic climate solutions.

This article is categorized under:
Science of Water > Water and Environmental Change
Engineering Water > Water, Health, and Sanitation
Human Water > Value of Water

KEYWORDS

energy; environment; food and agriculture; nexus; water, sanitation, and hygiene

1 | INTRODUCTION

Water-related news coverage spans the globe, from water shortages in Jordan and the Southwest United States to pollution concerns in New Zealand and new dams built in China and Ethiopia (Al Jazeera, 2023). At the same time, information about climate change, from increasing temperatures and extreme weather events to climate actions and responses,

is also in the news. Threats to water quality and availability are a primary way that climate impacts are felt by people and society, highlighting the importance of thinking about the "water–climate nexus" (i.e., the intersections between water, climate change impacts, and climate solutions).

This Primer serves as an introduction to the water-climate nexus by drawing on systems thinking and sectoral interactions. We begin with an overview of water security and systems thinking (Section 2). We then describe the many important roles that water plays in supporting various environmental and societal activities (Section 3). For this Primer, we focus on water's roles across four key sectors: environment; drinking water, sanitation, and hygiene (WASH); food and agriculture; and energy. These sectors not only represent important uses of water, but are also very likely to be substantially affected by climate change and the human response to climate change.[1] It is particularly important to understand how these four sectors interact with water resources and each other when designing solutions that aim to mitigate and adapt to climate change. A summary of the various ways that climate change is accelerating and exacerbating water issues (including water quantity, water quality, and interactions with society) is presented for the four sectors in Section 4.

We then demonstrate the need for climate solutions to use a systems approach and introduce a set of guiding questions that consider the role of water as an integral resource across sectors (Section 5). We conclude by emphasizing the need to reimagine how we approach water security priorities within possible climate solutions (Section 6). While an exhaustive discussion of all relevant intersections between water and climate is outside the scope of this work, we hope this Primer provides a solid foundation for undergraduate and graduate students, practitioners, and researchers to consider the interconnectedness of the water–climate nexus more actively in their ongoing studies and practice.

2 | WATER SECURITY AND SYSTEMS THINKING

Water security is defined as safeguarding sustainable access to sufficient quantities of water of acceptable quality for human well-being and ecosystems (United Nations, 2013). Water security spans multiple needs, from water for drinking and sanitation to related activities of food, energy, and land management, all of which are important to human health and ecosystem well-being (United Nations, 2023). The central role of water in meeting societal demands has become significantly amplified in recent decades due to the tremendous acceleration in use of natural resources and alterations to the natural environment by human activities (Folke et al., 2021; Lewis & Maslin, 2015).

Projections indicate that the gap between water supply and demand will continue to widen. Current projections indicate up to 40% of current water demands could be unmet as early as 2030 (UNEP, 2023); these gaps are expected to be further exacerbated by climate change (Pokhrel et al., 2021). Increasing awareness of these issues has prompted efforts to use more holistic approaches in water-related research and policy (e.g., Montanari et al., 2013). Concepts such as "Integrated Water Resources Management" and "One Water" have been introduced to consider water resources in a comprehensive manner (Dirwai et al., 2021; Gude, 2021). Similarly, scientists have started to work across disciplines to understand ways that physical and social systems around water interact with each other (Linton & Budds, 2014; Ross & Chang, 2020), which has facilitated our understanding of the role of economics, communications, and social structures on water processes in practice (Gunda et al., 2018; Müller & Levy, 2019). Datasets and websites are also being developed to improve information sharing with citizens and across water sectors (SWRC, 2023; Pekel et al., 2016).

Despite these many efforts, water is often still addressed in a siloed way, if at all, when it comes to climate change and climate solutions. Instead, a systems approach—which considers interactions between individual components to understand overall outcomes (Meadows, 2008)—is needed to characterize current water–climate dynamics and inform possible solutions. Calls for systems thinking in water are by no means new, but in practice, siloed thinking and action persist. Systems thinking requires interdisciplinary research, which can be challenging when teams are working with vague or ambiguous definitions and lack the knowledge and skills to effectively bridge silos (Kirschke et al., 2016; Medema et al., 2008).

In the sections that follow, we examine some of the ways in which climate and water interact within and across sectors. Understanding how actions or efforts in one sector may impact or be impacted by other sectors can help to promote systems thinking at the water–climate nexus. We make the case for an approach that holistically considers both physical and social dimensions of water when developing needed climate solutions.

3 | HOW DOES WATER INTERFACE WITH ENVIRONMENTAL AND HUMAN ACTIVITIES?

Water influences every facet of human well-being, from how we grow our food and power our homes to the subsequent environmental impacts of these activities. We examine the water–climate nexus in the context of four key interacting sectors: water for environment; water for WASH; water for food and agriculture; and water for energy (Figure 1). In this section we begin by briefly describing issues of water quantity, quality, and societal dynamics in each of these sectors as well as across sectors.

3.1 | Water for environment

The vast majority of water (96.6%) on Earth is in oceans, with only 3.4% captured in fresh water (including glaciers, groundwater, and surface water) (USGS, 2018). All of these waters play a critical role in shaping landscapes, including vegetation and topographies (Bernacchi & VanLoocke, 2015; Gardner, 2020). Water availability in the environment has shaped the course of human history around the world (Meyer & Turner II, 1994). Humans have also altered flows and

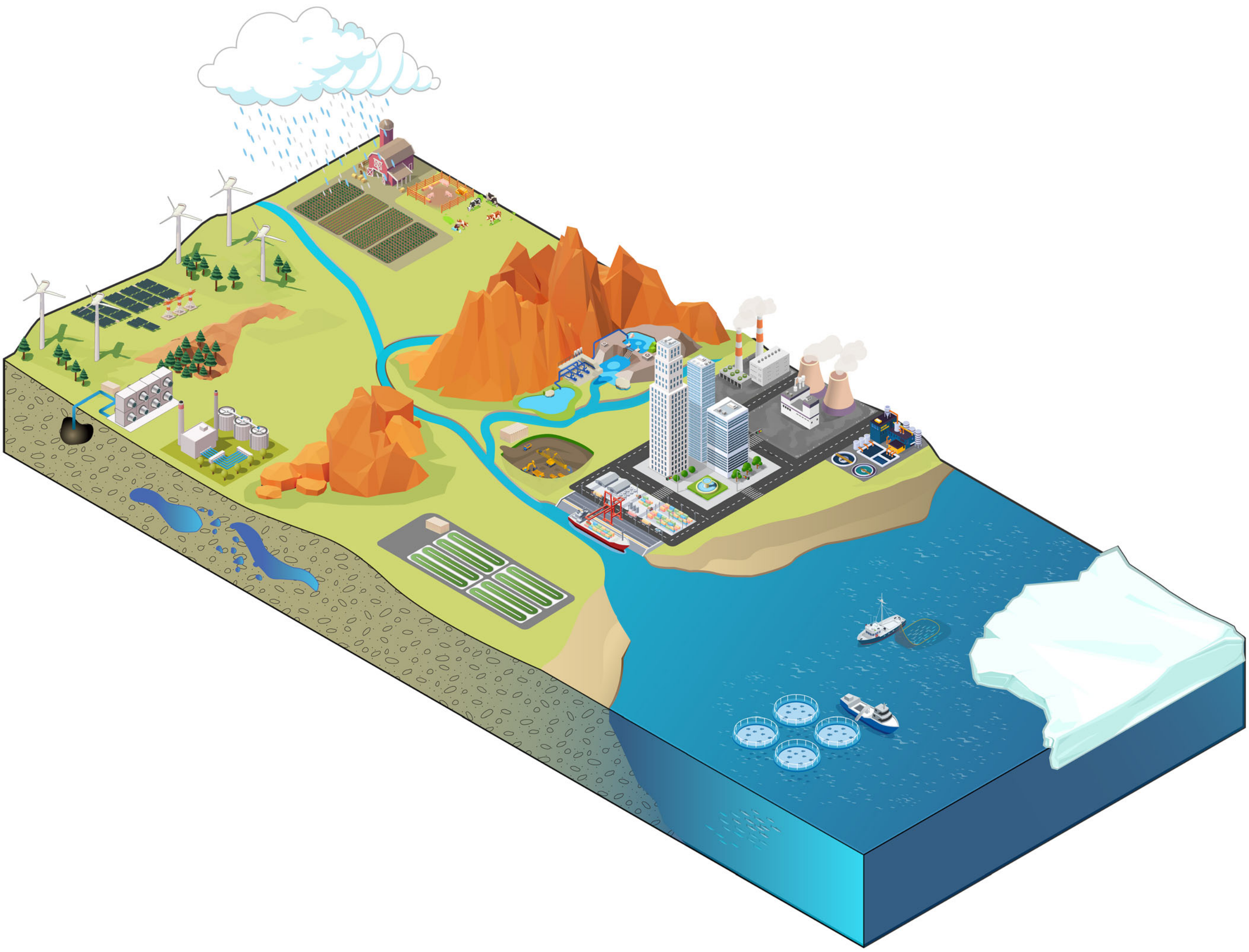

FIGURE 1 Diagram showing the various ways that water interfaces with natural and human activities. Water is present in various forms (e.g., ice, surface water, and ground water) across landscapes and is critical to various sectors, such as: topography and distribution of vegetation (environmental sector); treatment and distribution of water and wastewater (WASH sector); growth of crops and fish (food and agriculture sector); and generating electricity and heat (energy sector). The interactions between water and the sectors are dependent on local water availability, can impact water quality, and are influenced by societal practices, including governance.

moved water for thousands of years, with dramatic alterations to terrestrial and oceanic water dynamics occurring over the last few centuries (Crain et al., 2008; Lewis & Maslin, 2015). For example, a global evaluation of river flows identified that water withdrawals and damming of rivers have led to significant impacts on environmental flows (Döll et al., 2009; Virkki et al., 2022). Human impacts also extend to groundwater sources, which have been experiencing declining levels around the world and saltwater intrusion in coastal aquifers (Agoubi, 2021; Jasechko & Perrone, 2021). Land subsidence and earthquakes have also resulted from extraction and injection of water resources into the ground (Gorelick & Zheng, 2015). Introduction of salts and nutrients from human activities have led to widespread degradation in freshwater quality, leading to harmful algal blooms, fish kills, and other impacts (Chislock et al., 2013). The presence of waste products (e.g., plastics) and biological and chemical pollution (e.g., nutrients and manufactured chemicals) in water bodies from human activities are also becoming more widely observed (Landrigan et al., 2020). In response, there are many attempts to improve the protection of water bodies around the world, often led by Indigenous people and other local communities, such as some regions granting rights to rivers (Tănăsescu, 2020).

3.2 | Water for drinking, sanitation, and hygiene (WASH)

Access to WASH services is recognized as a fundamental human right (United Nations, 2010). Although the global share of freshwater withdrawals used for centralized WASH services is modest (11%), it is estimated that in 2030, 1.6 billion people will be without access to potable water, 2.8 billion without safely managed sanitation services, and 1.9 billion without basic hygiene facilities (Ritchie et al., 2023; United Nations, 2023). WASH services are vital to hydration, hygiene (such as hand washing and bathing), and domestic uses (such as preparing food), all of which are essential to human well-being and reducing the global burden of acute and chronic illnesses. Water often must be treated to be drinkable. Treatment practices for WASH vary based on the source of water (e.g., surface water, springs, groundwater, rainwater, seawater), the relative location within watersheds, local regulations, and the availability and quality of infrastructure (WHO, 2021). For example, in some regions, water is treated at point-of-use at the household level, such as through boiling or reverse osmosis (Garcia-Suarez et al., 2019) while other regions may have centralized, utility-scale treatment facilities staffed with professionals doing routine monitoring to comply with water quality standards (Ding et al., 2022). Similarly, techniques for managing wastewater can range from pit latrines and septic tanks for individual homes to centralized, utility-scale piped sewer system networks (CDC, 2022). Centralized water treatment systems require significant energy input to treat raw water and wastewater and to transport water through pipelines (Sanders & Webber, 2012; Zib et al., 2021). There are many current and future challenges to WASH, including system operations and maintenance of aging infrastructure; concerns regarding water availability and water access; ethical and economic debates regarding the commodification of WASH services; and issues of emerging contaminants that require increasingly complex and costly water treatment (Nedjoh et al., 2003; Pacific Institute, 2010).

3.3 | Water for food and agriculture

Globally, agricultural production is the largest user of fresh water, accounting for about 70% of water withdrawals worldwide across both surface and groundwater sources (Zhang et al., 2022). Water for food includes not only the use of fresh water for crop irrigation and livestock production, but also rainwater, rivers, and seawater that support wild harvested fish, shellfish, and aquaculture. In addition to supporting food security, water is also used to support the production of fibers and biofuels (Bryan et al., 2010). While many Indigenous and other smallholder food systems around the world have and continue to utilize water sustainably (Leonard et al., 2023; Mabry, 1996), standard practices for large-scale and industrial agriculture frequently lead to excessive water use, depleting surface and groundwater systems in many areas around the world (Gleick, 2000). Frameworks for measuring the amount of water embodied in a product, like "virtual water" or the "water footprint," are commonly used to compare water intensity of agricultural crops (Dalin et al., 2012; Mekonnen & Hoekstra, 2011). These calculations show that production of animal products is water intensive, and that industrial animal production is far more responsible for consumption and pollution of water resources than lower-intensity grazing systems (Mekonnen & Hoekstra, 2012). Agricultural production can also lead to pollution of surface water and groundwater sources through the use of fertilizers, land application of manure, herbicides, and pesticides; these water quality impacts can lead to eutrophication, harmful algal blooms, and damage to aquatic ecosystems (Evans et al., 2019; Hellerstein et al., 2019). These impacts can cascade to other sectors, leading to increased costs

for drinking water treatment and land use changes that influence wildlife habitat (D'Odorico et al., 2018; Loecke et al., 2017; Otto et al., 2016).

3.4 | Water for energy

Energy can be provided through various resources (including biomass, fossil fuels, wind, solar, and water itself) for end uses that vary greatly in scale and dependence on water (IEA, 2020). For example, energy for household cooking might involve wood (which requires water for growing), natural gas (which requires water for producing and may also generate "produced water," which refers to often highly saline fossil water found in natural gas formations), or electricity. Electricity can be made from essentially any energy resource, with diverse water needs: for example, generation of electricity may require water for thermoelectric cooling, hydropower generation, or mining of fuels and critical minerals (Cousins et al., 2024; Hamiche et al., 2016). In the United States, water use for energy systems, including energy resource production, cooling, and pollution controls, accounts for 40% of all water withdrawals and 10% of total water consumption (Grubert & Sanders, 2018). Energy-related water use is unusual in that facilities commonly withdraw large volumes of water (e.g., for thermoelectric power plant cooling) and almost immediately discharge it. Although these activities (termed "non-consumptive") do not reduce the total volume of water available, they do impact water temperature and how much water is available at what time and location, which in turn can impact aquatic and marine life (Logan et al., 2021; Lubega & Stillwell, 2018). These impacts can exacerbate water stress: for example, power plants likely need more water for cooling during a midsummer heat wave under drought conditions when air conditioning demand, and thus power demand, is high. Much of the global transportation system also relies on water, either for supporting production of fuels (King & Webber, 2008) or to support shipping on waterways (Andersson et al., 2016).

3.5 | Water across sectors

The four sectors that we have described often interact with one another. For example, construction of dams, which interrupt flow regimes of natural rivers, is frequently motivated by energy production (e.g., hydropower) and agricultural needs (e.g., storage of water for irrigation) (Lehner et al., 2011). Pollution from energy, agriculture, and industry impacts the quality of water in the environment (e.g., temperature, nutrients, and chemicals) (D'Odorico et al., 2018). Changes in land use from agriculture and energy-related mining also impact water flows and quality (D'Odorico et al., 2018; Northey et al., 2016). Many of the water-related interactions between agriculture, WASH, and energy sectors are moderated through water in the environment. For example, increased contaminant levels in water bodies from agriculture can increase treatment and costs required to ensure safe drinking water, and consequently, associated energy inputs for treatment. Since energy production typically also relies on water, treatment of water (which itself relies on energy) can impact water availability and quality in other locations. As another example, increased groundwater pumping to support agriculture requires energy, and can impact the availability of water for domestic household wells as groundwater levels decline.

4 | HOW IS CLIMATE CHANGE IMPACTING WATER DYNAMICS ACROSS SECTORS?

The current climate is changing (Box 1). Impacts to the water cycle are one of the main ways humans experience climate change. Climate impacts are expected to decrease freshwater availability and quality for many regions of the world and increase the frequency of extreme weather events (Ullah et al., 2022). These stresses often exceed local capacities for adaptations, further reinforcing the connections between water sectors. The specific dynamics and potential impacts of the water–climate nexus are highly variable worldwide, based not only on natural factors (e.g., precipitation, temperature, and soils) but also on human factors (e.g., demographics, culture, and governance). The following subsections describe the various ways that climate change is already or will be impacting water-related systems in greater detail.

BOX 1 Overview of climate change

Climate change refers to the long-term shifts in weather patterns observed on the planet. Although there are natural causes (e.g., shifts in the solar cycle or volcanoes) that can cause the climate to change, the current changes are due to human activities that have generated significant greenhouse gas emissions (e.g., carbon dioxide and methane) that trap heat within the Earth's atmosphere and oceans (Bonfils et al., 2020). These emissions, which stem from various activities (e.g., energy production, manufacturing, and large-scale agriculture) have led to increased warming of the Earth that has been linked to a number of other processes, including shifts in atmospheric and hydrological dynamics (Folke et al., 2021) that will adversely affect ecosystems (Hadi, 2019) and planetary health (Landrigan et al., 2020). In addition to empirical observations, computer simulations are heavily used to understand possible impacts of climate change, especially in concert with possible socio-economic pathways (IPCC, 2021). However, there are still many unknowns regarding the current changing climate, particularly concerning cascading and downstream effects (Schwarzwald & Lenssen, 2022). These gaps have motivated researchers to explore possible catastrophic scenarios (Kemp et al., 2022) as well as continue to advance new techniques for Earth system prediction (e.g., through the integration of artificial intelligence methods; Hickmon et al., 2022). For additional information about climate change, please consult IPCC (2023).

4.1 | Climate and water for environment

Water is one of the primary means through which climate change is expected to impact broader Earth system dynamics, both on land and in oceans. For example, increased temperatures are leading to shrinking of glaciers and thawing of permafrost, ocean warming and acidification, and sea level rise (IPCC, 2019). Climate change is shifting precipitation patterns, resulting in net reductions in precipitation (including loss of snowpack) in some areas and net increases in others (Bador & Alexander, 2022). Precipitation is also generally expected to occur in more intense bursts, leading to increases in frequency of both severe droughts and intense flooding from storms and other extreme events, sometimes in the same regions (Bador & Alexander, 2022). These intense swings between conditions, termed "weather whiplash," impact both soil moisture storage and nutrient dynamics (Loecke et al., 2017). Reduced capacity for water storage (Pokhrel et al., 2021) and warmer temperatures on land are expected to lead to aridification (Overpeck & Udall, 2020), which has implications for wildfire intensity and subsequent downstream effects on water and soils (Williams et al., 2022). Changing precipitation, increasing temperatures, and nutrient mobilization are also expected to influence vegetation dynamics (from forests to estuarine systems) as well as exacerbate existing issues, such as harmful algal blooms (Gobler, 2020; Hesterberg et al., 2022; Montefiore et al., 2023; Wunderling et al., 2022). These rapid transformations of the environment (e.g., thawing of permafrost and changing migration patterns of species) are expected to increase the incidence of known diseases, introduce new pathogens, and change disease propagation patterns, all of which threaten animal and human health (Mora et al., 2022; Yarzábal et al., 2021).

4.2 | Climate and water for drinking, sanitation, and hygiene

The availability and quality of fresh water supply sources used for WASH services are also impacted by climate change dynamics (Robbins Schug et al., 2023) and can lead to adverse human health effects (Levy et al., 2018). For example, a prolonged decrease in precipitation or increase in temperature can result in drought conditions, which can contribute to increased salinity and other pollutants in drinking water (Hadi, 2019). If not properly treated, high salinity in drinking water is associated with increased blood pressure and chronic kidney disease (Talukder et al., 2016). Sensitive subpopulations (e.g., persons with cardiovascular disease, diabetes, and end-stage renal disease) are at higher risk for adverse health complications associated with increased salinity in WASH services (Khan et al., 2020). Heavy precipitation can increase the potential of waterborne disease and vector-borne disease burden, by transporting pathogens in untreated sewage to drinking water sources, including groundwater that supplies public and private wells (Bastaraud et al., 2020; Lindgren et al., 2012; Tidman et al., 2021). Significant precipitation (especially after drought conditions)

can also disturb heavy metals (e.g., lead) and mobilize nutrients (e.g., nitrogen) in soils, resulting in the transport of these pollutants into water sources used for drinking water, leading to increased treatment costs (Khayan et al., 2019; Loecke et al., 2017). Increasing intensity of weather events can also lead to infrastructure being damaged or overwhelmed (Landsman et al., 2019), while sea level rise can create challenges for WASH operations in river deltas, low lying valleys, and coastal aquifers (IPCC, 2022). Although infrastructure can be designed to stand up to heavy storm and wind events, the frequency and compounding nature of climate shocks are expected to amplify existing inequities in WASH services for communities around the world (Ahmad et al., 2018; McDonald & Jones, 2018; Niles & Salerno, 2018). Furthermore, climate change could potentially contribute to an increase in emerging infections (e.g., Lyme borreliosis) and neglected tropical diseases (e.g., Schistosomiasis), presenting additional challenges for low- and middle-income countries (Howard et al., 2021).

4.3 | Climate and water for food and agriculture

Agricultural systems are increasingly impacted by drought, storms, flooding, hurricanes, heat waves, fires, and other disasters. These impacts will be amplified by climate change due to increased extreme weather events (Anwar et al., 2013). For example, livestock waste management systems are often not designed to consider extreme events such as flooding and hurricanes, leading to discharges of pollution into water bodies (Stoddard & Hovorka, 2019). Other extreme events, such as heat waves and drought, can stress both plants and animals leading to crop failures and livestock deaths (Lesk et al., 2022). Changes to temperature and moisture patterns can also result in higher disease pressures (e.g., insects and fungus) or shifting distribution of crops and livestock (Chakraborty et al., 2000). Soils can be affected by issues like increasing salinity and the persistence of soil pathogens, which can impact agriculture and human health. Climate change-induced drought can increase water use for irrigation, further driving groundwater depletion when surface water supplies are lower than demands (Famiglietti, 2014). Flooding also impacts food security, with large variations observed in different geographic regions (Reed et al., 2022). Importantly, these impacts are often felt inequitably, with more negative impacts at local scales. For example, salmon populations in the Pacific Northwest region of the United States have declined significantly because of both climate change and dams constructed for agricultural irrigation and transportation, to the detriment of the health of Indigenous people (Norgaard, 2019). Exposure to these extreme events is also motivating farmers across various regions of the world to migrate away from farmlands to urban regions or even across borders (e.g., Fishman & Li, 2022; Nguyen & Sean, 2021). Climate change can also impact the health and safety of people involved in agricultural labor, through increased exposure to heat and wildfire smoke (Marlier et al., 2022) and making farmworker communities more prone to flooding (Rust, 2023). While agriculture is a major contributor to climate change, it is also increasingly being considered as a way to mitigate climate change through methods such as conservation agriculture and soil carbon sequestration, although the efficacy of these strategies for climate mitigation is not fully understood (Powlson et al., 2014).

4.4 | Climate and water for energy

The intersections between the energy sector, water, and climate change are highly variable, with widely different water issues across energy systems in different locations and regions. Climate change is expected to directly affect energy systems in multiple ways, including reductions in the amount of water available for hydropower and thermoelectric production (van Vliet et al., 2016) and disruptions to production during extreme weather events (Gargani, 2022; Jordaan et al., 2019; Verchick & Lyster, 2021). But arguably, the most significant impact of climate change on the energy sector is that climate change is motivating energy transitions from predominantly fossil fuel-based systems toward predominantly zero-carbon systems. The combined effect of climate change and energy transitions is expected to pose challenges for water resources planning and management (Grubert & Marshall, 2021). Shifts in types of energy systems can change water demands and water quality impacts (Cousins et al., 2024; Tarroja et al., 2020). For example, some energy sources like wind require little water for operations, while others like biofuels, hydrogen, and synthetic liquid fuels can be water intensive (Grubert, 2023). Demand for mined materials, like lithium for electric vehicle batteries, will also shift demand for water resources, with potentially significant impacts on water quality and quantity in certain places (Blair et al., 2024; Sovacool et al., 2020). Similar to the other sectors described in this article, there are many water-related

equity and justice concerns within the energy sector, frequently related to issues of water access, resource management, and water quality impacts (LeQuesne, 2019; McCauley & Heffron, 2018; Mills-Novoa et al., 2022; Sovacool et al., 2020).

4.5 | Climate and water across sectors

Given the many intersections between water and environment, WASH, agriculture, and energy, climate change impacts in one sector will influence dynamics in the others as well. For example, weather whiplash events over agricultural lands in the midwestern United States have increased the mobilization of contaminants from soils into water bodies, impacting local water quality. Subsequently, these water bodies, which serve as drinking water sources, have required more treatment, which has led to increased energy usage, increasing water rates for customers (Loecke et al., 2017). Changing temperature and precipitation patterns also impact the availability of water for energy production. For example, a heatwave in Summer 2022 in China led to increases in energy demand for cooling, but a concurrent drought in the region led to reduced hydropower production, which led to power shortages and outages across the country (Zhao, 2023). Disruptions in power can further cascade into other sectors, impacting the ability of regions to treat water for household needs. In addition to short-term stresses on local communities, climate change can drive long-term changes like aridification, and can increase tensions between agricultural water users (often the largest users) and other water users (Wu et al., 2023).

5 | HOW CAN WE MOVE TOWARD MORE INTEGRATED SOLUTIONS?

Many solutions are being pursued to combat climate change, including policy changes, financial investments, and technological approaches (NASEM, 2023). However, if not considered holistically, these solutions run the risk of being one-dimensional, and can miss opportunities for cross-cutting novel solutions—or even generate unintended adverse consequences. A more intentional, multi-sector approach is needed in order to fully understand the dynamics of proposed solutions at the water–climate nexus. This approach includes consideration of interconnected resource demands associated with a solution (e.g., amount of water and energy for operations); the scale at which that solution is implemented (e.g., centralized or decentralized, rural vs. urban, and local vs. national); possible impacts to other sectors (e.g., environment, WASH, food and agriculture, and energy); and societal and cultural dimensions (e.g., workforce development and inequitable or unjust distribution of burdens and benefits).

For any climate solution, explicitly recognizing the broader interconnections with water (including equity, justice, scale, and geography) is imperative for success, since solutions may otherwise involve trade-offs with uneven consequences. For example, technologies geared toward decarbonization, such as lithium extraction for batteries, can create "green sacrifice zones," impacting water quality and quantity and risking the reproduction of colonial dynamics (Blair et al., 2024; Turley et al., 2022; Zografos & Robbins, 2020). The scale of solutions matters as well. For example, new water treatment solutions that are centralized at a municipal level versus highly decentralized at a household level (e.g., Rabaey et al., 2020) differ in accessibility, resilience, and the cost of implementation and maintenance in complex ways. Geography also matters because place-based solutions might be an appropriate technology in one climate, culture, or location but unworkable or unadvisable in a different place. Table 1 contains an initial set of guiding questions that can be used to consider the various factors of proposed solutions in the context of the larger water–climate system.

To demonstrate the implementation of the questions in Table 1, we developed a causal loop diagram that captures some of the important dimensions to consider for one illustrative example, desalination technologies (Figure 2). Desalination aims to tackle the problem of water scarcity through treatment of water with high salinity (e.g., seawater). However, as this visual illustrates, desalination technologies present several issues spanning environment, energy, just distribution of water, and waste management (Elsaid et al., 2020; Nassrullah et al., 2020; Stillwell et al., 2010). In particular, if the roll-out of desalination technologies ignores issues of affordability and accessibility for the most marginalized populations (e.g., low-income, unhoused, and housing insecure people; see Meehan et al. (2020)), then they do not solve water security issues. Given that the impacts of climate change tend to fall on those least responsible for causing it (Sultana, 2022), such equity considerations are crucial. Similar assessments could be conducted for many other climate change adaptation and mitigation-oriented solutions (e.g., carbon dioxide removal[2]).

While Table 1 and Figure 2 can serve as initial guides, we acknowledge that addressing interconnected challenges of water and climate change is complex and difficult, can vary from place to place, and there is no one-size-fits-all

TABLE 1 Guiding questions to promote cross-cutting water–climate solutions.

What is the primary objective of this solution?
Are resource demands from the solution flexible in time and space? How significant is potential resource competition, especially under scarcity conditions?
What scale is appropriate for implementation?
Are there possible impacts to domestic WASH services from this solution?
Are there possible impacts to food and agriculture production from this solution?
How much energy is required (or generated) to deploy and/or operate this solution? Does this energy contribute to energy injustice?
Are there wastes being generated from this solution? If yes, how are these wastes being released into the environment? What are the life cycle impacts of implementation, production and maintenance, disposal, and decommissioning?
Does a community have the expertise and the workforce to operate this solution? If not, is that being cultivated?
What type of unintended social, economic, and/or environmental consequences (including injustices) could occur from this solution? How might distribution of burdens and benefits shift under this solution?
How is the solution being tracked and monitored? What is the process for accountability?

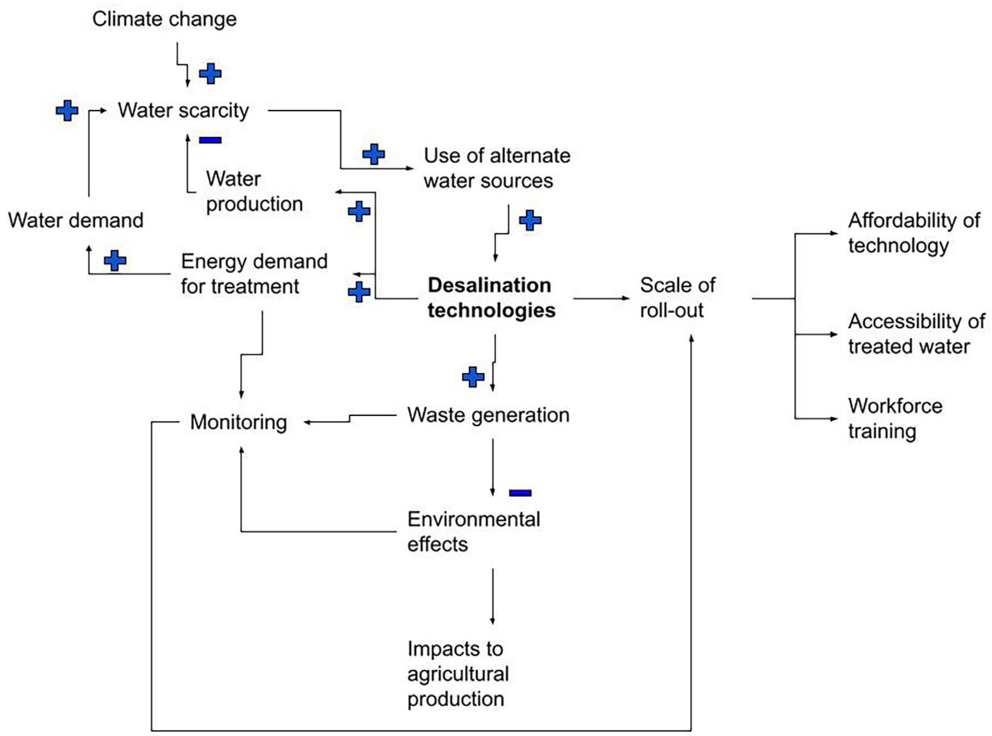

FIGURE 2 Example diagram showing the various ways that a solution oriented around desalination technologies could interact with other sectors through water. Arrows indicate connections between nodes in a specific direction. Plus signs indicate positive relationships between two nodes, while negative signs indicate an inverse relationship based on existing literature. Directions of arrows are based on existing literature on desalination (e.g., Elsaid et al., 2020; Nassrullah et al., 2020; Stillwell et al., 2010) as well as sources from other sectors referenced in Sections 3–5. Links without a specific direction indicate relationships that are either not clear in literature or yet to be established.

solution. In nearly every case, more research is needed to better understand how proposed climate solutions might impact water and communities. Additionally, we note the importance of equity in water–climate solutions. Disadvantaged communities already risk being disproportionately impacted by climate change itself (Benevolenza & DeRigne, 2019); without careful consideration, these same communities can be negatively impacted by intended or unintended consequences of climate solutions (e.g., lithium mining, as described earlier). We also recognize that water security and climate adaptation are expensive, requiring significant investment (Ritchie et al., 2023; World Bank, 2022). Thus, future

research could identify ways to better account for multi-sectoral costs and benefits throughout the life cycles of proposed climate solutions (Cordes, 2017; Mahmud et al., 2021).

6 | CONCLUSION

Water is an essential resource that supports both environmental functions and human needs, calling for a systems thinking approach to understanding interconnected issues at the water–climate nexus. Emerging climate solutions must intentionally take into account the impacts and interactions with water. To avoid unintended consequences and repetition of past mistakes, it is critical to understand how climate change impacts and associated solutions interact with water across multiple sectors, including environment, WASH, food and agriculture, and energy. Being mindful of the water impacts of proposed climate solutions and their local contexts is imperative for developing holistic approaches considering water–climate nexus governance, education, research, and practice. Any solution that creates or exacerbates inequality or benefits a select few, while resulting in additional burdens for communities already marginalized, must be challenged. Just as climate solutions are frequently evaluated based on their financial costs, they should also be assessed for other impacts, including impacts on water that look across multiple sectors. Such considerations of the water–climate nexus can help us better move toward equitable and resilient solutions.

AUTHOR CONTRIBUTIONS

Thushara Gunda: Conceptualization (lead); visualization (equal); writing – original draft (equal); writing - review & editing (equal). **Alida A. Cantor:** Conceptualization (equal); visualization (equal); writing – original draft (equal); writing - review & editing (equal). **Emily Grubert:** Conceptualization (equal); visualization (equal); writing – original draft (equal); writing - reviewing & editing (equal). **Angela R. Harris:** Conceptualization (equal); writing - review & editing (equal). **Yolanda J. McDonald:** Conceptualization (equal); visualization (equal); writing – original draft (equal); writing - review & editing (equal).

ACKNOWLEDGMENTS

The authors would like to thank Manny Rubio for support with the figure development and Raquel Valdez for reviewing an earlier version of the manuscript. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC (NTESS), a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration (DOE/NNSA) under contract DE-NA0003525. Any subjective views or opinions that might be expressed in the written work do not necessarily represent the views of the U.S. Government.

FUNDING INFORMATION

None.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] While other sectors also use water (e.g., manufacturing, industrial, transportation), their interactions with climate change and climate solutions generally occur through the environment and energy sectors.

[2] Carbon dioxide removal (CDR) has widely variable implications for water demand. CDR approaches that inject carbonated water into rocks or deep saline aquifers could influence environmental processes, and the operation of CDR facilities could increase competition for resources (particularly energy) that could impact WASH and food and agriculture sectors (Dupla et al., 2023).

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How to cite this article: Gunda, T., Cantor, A. A., Grubert, E., Harris, A. R., & McDonald, Y. J. (2024). The water–climate nexus: Intersections across sectors. *WIREs Water*, e1759. https://doi.org/10.1002/wat2.1759